GLOW DISCHARGE STABILITY IN PULSED ELECTRIC LASERS

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Introduction

The work reported in this paper is part of an ongoing effort among the Air Force Weapons Laboratory (AFWL), Tetra Corporation, and Ecodynamics Research Associates, Inc. to model electric fields in pulsed power devices and to understand glow discharge stability. The two companion papers discuss our progress in electric field modeling, while here we discuss progress in the glow discharge stability problem.

Over the years since electric discharge lasers were first developed, many investigators have experimentally and theoretically addressed the problem of discharge stability in pulsed and CW electric lasers. Collapse of the glow discharge is the prime limiting factor on power loading and hence power output on electric lasers. Experimentally, investigators have found that the condition of the electrodes, detailed shaping of the electrode, uniformity of the electric fields, uniformity of preionization, and gas mixture all have an effect on discharge stability. Theoretically, several investigators have addressed the issue of glow discharge stability in electric lasers, including the work of Nighan.[1] D. H. Douglas-Hamilton of AVCO has studied the process of streamer formation in pulsed electric lasers as part of an effort to understand discharge stability.[2] In this paper we discuss experimental evidence for a relationship between vibrational manifold energy and electron swarm energy distribution that appears to be important in determining discharge stability in pulsed molecular electric lasers.

Specifically, we report some observations on the scaling of discharge energy loading in pulsed electric lasers as a function of gas mixture and pulse length. These observations resulted from the study of data from five different pulsed electric discharge devices operated over a wide range of conditions and gas mixtures. The observations resulted from an attempt to derive a common base of understanding of the discharge stability characteristics of these five devices. The devices include three devices that are UV-initiated self-sustained discharges, and two that are e-beam controlled discharges. One of the e-beam controlled devices was a supersonic device operating at cryogenic gas temperatures. The densities range from .4 amagat to 1 amagat. (An amagat is standard density at 760 Torr and 0°C.). The gas mixtures range from a small fraction of molecular content to almost pure molecular content with CO_2, N_2, and CO molecular species.

The analysis was generated by the suggestion of a colleague that pulsed CO_2 lasers scale in energy loading by the energy loaded into the molecular content of the gas. That is, that the joules per liter-amagat loaded into the molecular species of the gas at the arc limit remains essentially constant for pulsed electric lasers.

Devices

Experimental data for five devices were studied to develop the scaling relationships presented in this paper. The devices were:

1. The ten liter Simplex CO_2 laser at Westinghouse which uses an ultraviolet-initiated self-sustained discharge.[3]

2. The 0.3 liter laser radar device built by Westinghouse and delivered to the Naval Surface Weapons Center.[4]

3. The 1.0 liter bell-jar developed at Westinghouse for discharge studies. This is a UV-initiated self-sustained discharge device.[5]

4. The 4.0 liter e-beam controlled-discharge Humdinger Jr. CO_2 laser developed at AVCO.[6]

5. The 2.6 liter supersonic CO laser (SCOL) developed at Boeing. This is an e-beam controlled discharge device.[7]

From each of these references, pertinent data were selected and reduced to determine the specific energy loaded in joules per liter amagat of the molecular content and the fraction molecular content of the gas. Only data taken under repeatable, controlled conditions near the arc limit were used in this study. Only data that are reasonably indicative of the characteristic arc limit of the gas and are not overly dependent upon device-dependent arc limits that might result from incomplete device engineering were used. Data and devices were chosen that showed the change in energy loading with changes in gas mixture for a single device, to separate out influences from device-dependent characteristics. Also, only data that are reasonably well documented and available in the literature are included.

Discharge Loading Data

Table 1 shows data taken on the 10 liter Simplex device at Westinghouse. The specific energy loading was found by calculating the energy loading into the gas from the laser output data and the efficiency, and then normalizing it to the molecular gas content to derive the specific energy loaded in terms of joules per liter amagat of molecular content. For the most part the tripropylamine seeded data were used with one sample of the unseeded data used. In general only those shots were used in which the maximum energy presented represents a pulse that does not arc during the pulse. The pulse forming network was set for 12.4 microseconds pulse duration and so only those shots that ran for 12.4 microseconds are included.

Table 2 shows discharge data from the other devices. These data were reduced in the same way to determine the specific energy loaded in terms

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Mixture	Concentration (%)				% mol	P_T	ε(%)	$E_{OUT}(J)$	$\tau_d(\mu sec)$		J_{IN}
$CO_2:N_2:He:H_2$	CO_2	N_2	He	H_2		Torr	Slope	Max	Max	Ave	l-am-mol
1:7:24:0.83*	3.0	21.0	73.5	2.5	26.5	800	18.1	293	12.4	8.2	580
1:12:20:0.83	3.0	35.5	59.9	2.5	41.0	798	17.5	343	12.4	12.1	455
1:7:18:0.66	3.7	26.3	67.5	2.5	32.5	800	19.0	378	12.4	11.5	582
1:5:20:0.7	3.8	18.7	75.0	2.5	25.0	800	19.0	222	12.4	11.9	444
1:9:16:0.66	3.8	33.7	60.0	2.5	40.0	800	18.2	330	12.4	12.4	431
1:10:7:0.5	4.4	54.0	39.9	2.6	61.0	795	18.0	392	12.4	12.4	341
1:7:12:0.5	4.9	34.1	58.5	2.5	41.5	800	20.0	370	12.4	12.4	423
1:4:12:0.3	5.7	23.0	68.8	2.5	31.2	785	20.0	383	12.4	12.4	594
1:12:4:0.45	5.7	68.9	22.9	2.5	77.1	785	18.8	301	12.4	12.1	201
1:7:8:0.24	6.1	42.7	48.7	2.5	51.3	788	20.0	444	12.4	12.3	417
1:5:6:0.24	8.1	40.6	48.8	2.5	51.2	800	21.2	409	12.4	11.9	330
1:7:4:0.3	8.1	56.9	32.5	2.5	67.5	800	20.5	427	12.4	10.6	293
1:9:2:0.24	8.1	73.1	16.3	2.5	83.7	800	22.0	482	12.4	9.2	249
1:7:2:0.25	9.8	68.2	19.5	2.5	80.5	800	22.0	400	12.4	8.2	215
1:8:1:0.25	9.8	77.9	9.8	2.5	90.2	800	20.6	339	12.4	9.5	173

$(T = 35\%, \bar{a} \sim 1.5\%)$ - Reference 3.

TABLE 1. LASER OUTPUT DATA OBTAINED ON THE 10 LITER MARK IV SIMPLEX STRUCTURE.

VOLUME	GAP	PRESSURE/DENSITY	MIX	TOTAL ENERGY LOADED	SPECIFIC ENERGY LOADED J/l-am-mol	% MOLECULAR	Ref.
0.3 L	2.0 cm	466 Torr	1-3 CO_2/He	19.6 j.	426	25.0%	4
1.0 L	8.0 cm	740 Torr	70-2-2-He-Ar-CO_2	140 j.	5325	2.7%	5
1.0 L	8.0 cm	730 Torr	70-2-1 He-Ar-CO_2	100 j.	7436	1.4%	5
1.0 L	8.0 cm	750 Torr	70-2-3 He-Ar-CO_2	162 j.	4104	4.0%	5
4.0 L	4.0 cm	0.93 amagat	3-2-1 He-N_2-CO_2	918 j.	493	50.0%	6 AVCO
4.0 L	4.0 cm	0.91 am.	3-5-1 He-N_2-CO_2	1217 j.	507	66.0%	6
4.0 L	4.0 cm	1.27 am.	0-3-1 He-N_2-CO_2	1600 j.	315	100.0%	6
4.0 L	4.0 cm	1.23 am.	8-2-1 He-N_2-CO_2	712 j.	537	27.0%	6
2.6 L	6.7 cm	0.4 am.	15/75/10 CO/Ar/He	360	2308	15.0%	9 Boeing
2.6 L	6.7 cm	0.4 am.	15/75/10 (DROOP)	430	2760	15.0%	9
2.6 L	6.7 cm	0.5 am.	10/80/10 CO/Ne/He	173	1335	10.0%	9
2.6 L	6.7 cm	0.5 am.	10/80/10 (DROOP)	224	1725	10.0%	9
2.6 L	6.7 cm	1.0 am.	10/80/10	446	1717	10.0%	9
2.6 L	6.7 cm	1.0 am.	10/80/10 (DROOP)	511	1965	10.0%	9
2.6 L	6.7 cm	0.4 am.	13.5/67.5/9/10 CO/Ar/He/N_2	393	1609	23.5%	9
2.6 L	6.7 cm	0.4 am.	13.5/67.5/9/10 (DROOP)	478	1954	23.5%	9
2.6 L	6.7 cm	0.4 am.	14.25/71.25/9.5/5 CO/Ar/He/N_2 (DROOP)	469	2344	19.25%	9

TABLE 2. OTHER DISCHARGE DATA

of joules per liter amagat of the molecular content. The percentage of molecular content in the gas was also determined.

These data were then plotted as shown in Figure 1 on a log-log scale with specific energy loading as a function of gas molecular fraction. Note that the data fall along lines with similar slopes.

First consider the Simplex data on the lower end of the curve 1. Note how the data follow the slope of the curve. Adding in the bell-jar experiments (which are from the same type of discharge and same gases) at the upper (low molecular fraction) end confirms the functional dependence of the data. For reasons discussed below, we feel that the location of the neon SCOL data on the line is coincidental. Now consider the 3 argon SCOL drooped-voltage points and note that they fall on a line with a similar slope to curve 1. The 2 argon SCOL constant voltage points also fall on a line of the same slope.

The Humdinger Jr. data fall (reasonably) around a line of similar slope, but with significant scatter. This is not surprising as the data have large scatter due to the experimental cooling configuration and the data were also taken at different densities (see reference 6).

These data tend to suggest a mixture scaling relation of the form:

$$\varepsilon = \frac{K}{(Fm)^{0.92}} \qquad (1)$$

where E = specific molecular energy loading ~ joules per liter amagat

K = Device performance and diluent constant

Fm = Fraction molecular content

This relation does not address scaling with changes in pressure, but only addresses scaling in energy loading with changes in molecular content without changes in diluent species. As shown by the SCOL neon 0.5 and 1.0 amagat data, changes in density do have a slight effect on energy loading. The SCOL argon and neon data show that changes in diluent affect the energy loading.

The difference between the argon and neon data for the SCOL device cannot be explained by a change in the stopping power. As described later in this paper, the arc limit for a given gas mixture appears to be independent of the pulse length and is rather dependent only on the energy loading. The change in specific energy loading between the neon and argon data is more probably related to the way the diluent gas modifies the population distribution of the high energy portion of the electron swarm.

Thus, this analysis appears to yield a means of evaluating the influence of gas mixture on energy loading. A scaling law still needs to be developed to scale the location of the curve (the K parameter) with changes in device characteristics, or changes in diluent species. The data suggest that the form of the equation and the 0.92 exponent are somewhat fixed and are characteristic of the physics of the electric discharge loading. The 0.92 exponent is also suspiciously close to 1.0, with no theoretical basis for preferring 0.92 to 1.0. The constant "K" appears to be adjustable by changing device characteristics or diluent species as illustrated by the diluent

change in the SCOL experiments. Note also that this analysis is restricted to those gas mixtures that have fairly similar attachment and ionization cross sections. This is, the molecular constituents considered here were all CO_2, CO, and nitrogen with argon, neon, and helium diluents. No strong attaching gas mixtures, such as fluorine-bearing mixtures, were considered in this analysis. Note that these data imply that there is not a strong variation in the energy loading characteristics with subtle changes in the CO_2/nitrogen mixture as close examination of the Simplex data will indicate. Rather, the energy loading seems to be primarily a function of the molecular content. In contrast to earlier suggestions, the specific molecular energy loading is a function of the molecular fraction and is not a constant.

Pulse Length Scaling

The insight into pulse length scaling comes from two different sources. Dr. Lou Denes has indicated that changes in pulse length do not change the energy loading capability of the Simplex device at Westinghouse, certainly up to pulse widths in the 15-20 microsecond range.[8] This is the result of many experimental shots taken with laser extraction.[3] Similarly, the data shown in Figure 3, which is taken from Thoenes and Kurzius indicate the same type of behavior from the small scale pulsed CO_2 device at AVCO.[9] That is, the energy loading stays essentially constant as the pulse length changes. The data pertains to arcing in $CO_2/N_2/He$ = 1/2/3 ($E = 4.6 \cdot 10^3$ V/cm, $\rho_0 = 1$ atm, $T = 295°K$, $E/N = 1.85 \cdot 10^{-16}$ V cm^2) for varying discharge current density. Thus within a pulse width range where the cathode shock wave does not perturb significantly the discharge stability, the energy loading of the gas is not changed with pulse length. This holds over a wide range of current density, which implies that current density does not strongly affect discharge stability. This is consistent with our earlier suggestion that the key factor in determining discharge stability in well designed, well engineered pulsed electric lasers is a relationship between the vibrational manifold energy and the electron distribution in the gas.

Theoretical Considerations

A theory to describe this behavior has not yet been developed. Some speculation may be in order, however. If one plots the electron distribution function for two different gas mixtures with different molecular fractions and normalizes the E/N to the number density of the molecular species, one finds that the distribution functions have essentially the same shape as shown in Figure 4 taken from Reference 8. That is, the ratio of E/N's for comparable electron distributions will be the ratio of the molecular fraction. The prime difference lies in the high energy tail of the distribution. In Figure 4, note that the population of electrons above 2 ev is significantly higher for the 1:2:3 mixture. In studying the distribution function from this normalized point of view, the increase in helium content tends to reduce the magnitude of the high energy tail. Figure 1 indicates that as the diluent, usually helium, content increases so does the specific energy loading into the molecular species. This suggests that while the main portion of the distribution behaves in very similar fashion with similar molecular fraction, the high energy tail is the portion that is dominant in determining discharge stability. Hence, the discharge may be more stable in a specific energy loading sense with increased helium because of the suppression of the high energy electrons by the increased amount of helium.

The key issue in determining the discharge stability and hence the specific energy loading may in fact be the relationship between the vibrational temperature in the molecular species and the high energy tail of the electron swarm. The fact that the energy loading is essentially independent of the pulse width seems to suggest that the current density is not the limiting factor. The data also seem to indicate that the diluent species play an important role in determining energy loading through their function of affecting the shape of the high energy tail of the electron distribution. Since the specific energy loading can be translated to an energy loading per molecule it appears reasonable to suggest that discharge stability is primarily a function of a relationship between the average vibrational energy in the molecules and the average energy in the high energy portion of the electron swarm.

Further theoretical work is appropriate to try to determine the nature of that relationship.

Acknowledgements

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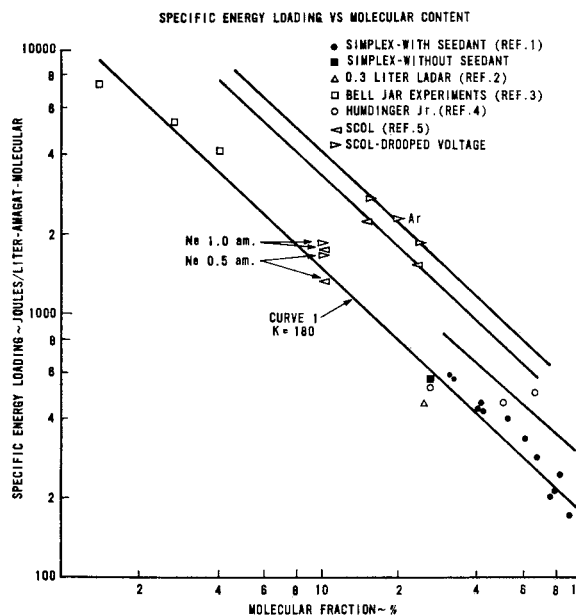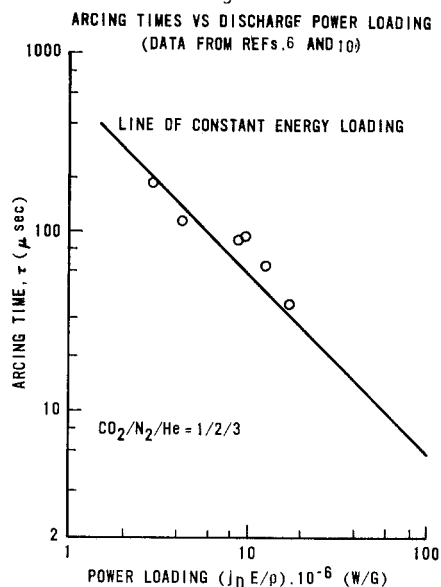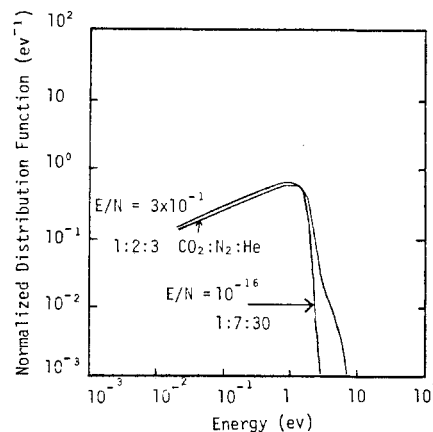

Figure 1

Figure 2

The distribution functions are normalized to the same E/N_m where N_m is the number of molecules, but excludes He atoms.

Figure 3